# Ocean Acoustic Propagation: Fluctuations and Coherence in Dynamically Active Shallow-Water Regions

Timothy F. Duda
Applied Ocean Physics and Engineering Department, MS 11
Woods Hole Oceanographic Institution, Woods Hole, MA 02543
phone: (508) 289-2495 fax: (508) 457-2194 email: tduda@whoi.edu

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## LONG TERM GOALS

The goals are to understand the nature and causes of acoustic signal fluctuations in the shallow water environment. This will allow prediction of acoustic system performance and exploitation of acoustic signal properties. Here, signal means any identifiable acoustic reception, including noise of unknown origin, identified signals, and intentional signals.

## OBJECTIVES

An objective is to gain understanding of the fluctuation behavior of fully three-dimensional acoustical propagation (including horizontal deflection from seafloor and water column inhomogeneities) in shallow-water environments with three-dimensional structure at all significant scales. This will allow evaluation of commonly used two-dimensional approximations for ocean structures and propagation physics. A second objective is to classify acoustic stability and fluctuation using signal parameters.

## APPROACH

To understand and predict shallow-water acoustic conditions, we (including collaborators) have been doing forward modeling and examining the effects of assorted oceanic features on acoustics. This is continuing under this grant. In addition, we are beginning a classification effort to find fundamentally different regimes of scattering that might be encountered in differing shallow-water environments using signal parameters. Such parameters are, for example, intensity variance of randomly chosen multipath amplitudes, variance of peak intensity selected from multipath interference patterns, and decorrelation time scales of these. This may be somewhat analogous to the lambda-phi diagrams of the deep-water acoustic fluctuation theories developed over the last few decades.

The effort is aimed at summer conditions in the temperate ocean. This is a stratified regime that is downward refracting acoustically, and which supports internal waves. Observations show that packets of nonlinear mode-one internal waves often dominate water column structure. Internal waves at a sound source control acoustic mode excitation, and thus the effects of mode-stripping on long propagation paths. Waves along the path can cause mode coupling, altering mode-stripping effects at further range. Long internal waves or internal tides can alter mode shapes and mode stripping, and can alter source excitation, but probably do not cause mode coupling.

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14. ABSTRACT
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15. SUBJECT TERMS

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The focus of modeling has thus far been sound propagation across fronts and across packets of nonlinear internal waves. Most simulation is done with the RAM 2-dimensional parabolic equation (PE) model. This was written by Mike Collins of NRL. We have modified the code by changing the input and output protocols to speed up operation and allow flexible examination of the output. This year we have developed and started using a 3-dimensional PE code (next section).

We are comparing our theoretically based ideas and model-derived results with ground-truth field observations. For instance, the ONR ASIAEX South China Sea study, which our group participated in, yielded four papers in the October 2004 *IEEE Journal of Oceanic Engineering* containing analysis of acoustic signals at 250-450 Hz from sources at ranges of 21 and 32 kilometers: Orr et al. [2004], Mignerey and Orr [2004], Chiu et al. [2004], and Duda et al. [2004]. The 2006 report on this project describes their results. These data are still being examined, plus new data from the recent Littoral Environmental Acoustics Research (LEAR) portion of the ONR Shallow-Water 2006 experiment (SW06) in the Mid-Atlantic Bight east of New Jersey on the shelf.

Regarding the classification work, the goal is to identify unique relate shallow-water fluctuation regimes, measured in terms of fluctuation parameter state vectors received by an array, and relate them to their causes (large internal waves, small internal waves, focusing by alignment with internal wave crests, etc.). The ability to classify the propagation domain (i.e. identify the cause of dominating fluctuations) would enable modeling, prediction, and extrapolation. This would be a through-the-sensor classification or inversion technique. A specific objective is a multi-parameter definition of signal characteristics which allows description of the fluctuations in terms of physical conditions, which would serve to condense the complicated effects of moving internals wave (and/or fronts) into meaningful and potentially predictable measures of acoustic signal parameters. At this time, a data clustering (cluster analysis) approach is under examination.

This year the project was expanded to include analysis of the spring 2007 ONR/Taiwan acoustics experiment in the ASIAEX area of the South China Sea. This work is just beginning at this time.

## WORK COMPLETED

This year, data clustering analysis was performed on ASIAEX fixed-path signals from the South-400 Hz source to the WHOI HVLA. The initial results have been discouraging, in that the data did not form distinct clusters of co-varying behavior. Parameters examined were second moments of pulse energy, width (time), and arrival delay, computed for each within half-day time windows. Further parameters and time windows will be examined in an effort to identify scattering signatures.

This year, we finished the three-dimensional parabolic equation (PE) code. At this time we are not using it in a mode that allows the density in the seafloor to differ from that of the water. Adjustment of the field output to include the effects of density discontinuities, using methods of Tappert and Smith, has been implemented in a test mode, but slows the code by 50% (it is a second parallel field computation), so it is not used routinely. The code and initial results obtained with it appear in a WHOI report issued in December, 2006. WHOI postdoc Y.-T. Lin has also been working with the code and modified it to allow a cross-range slope. A report was issued describing the SW06-LEAR experiment (Newhall et al, 2006).

## RESULTS

Using the 3D PE code, a situation exhibiting concurrent mode coupling and horizontal refraction of sound solely from internal waves was examined. The results were published in an Oceans ’07 (Aberdeen) paper. Figure 1 shows this result. One internal wave of the largest size seen in SW06 (20-m amplitude in water of 80-m depth) causes this effect. Mode coupling alone can be handled with 2D theory or simulation, and adiabatic mode refraction can be handled using a vertical mode horizontal ray (or horizontal PE) approach, but both occurring together demands a full 3D treatment.

Work has begun to examine propagation through curved internal waves using the 3D PE code (Figure 2). This research is currently underway. Focusing of sound into horizontal beams not aligned with the source is a possible effect (not shown by the figure; this is more likely to occur for waves with compound bends). Refraction of modes may vary strongly enough that internal waves may behave like prisms, separating modes.

Time series of internal tides and nonlinear internal wave packets were measured at many SW06 moorings. These each propagate (often in the same direction) at speeds of 0.7 to 0.8 m/s. The internal tides have wavelength of 25 to 40 km, whereas the nonlinear waves have 300 to 1200 m wavelengths. Using the time series to construct a realistic temporally evolving vertical slice of sound speed (similar to Chui et al 2004), time-varying signal level vs. range curves can be generated (Figure 3). These show strong variations. At 9 km range, depth-averaged signals can vary by 6 dB (depth averaging quantifies seafloor loss effects), with range-averaged single-depth arrivals being even more variable. The effects of varying mode excitation by the fixed-depth source, as well as that of varying mode attenuation parameters, are being examined for relative importance.

A paper was written for the Underwater Acoustic Measurements conference in Crete in June, 2007. Figure 4 shows measured WHOI horizontal-vertical line array (HVLA, L-array) 100-Hz arrivals from a 19.2 km distant source (Miami Sound Machine, H. DeFerrari), modal fits to the VLA signals, and synthetic HVLA signals constructed assuming fixed mode content. The sound arrives at approximately 26 degrees from endfire. The actual and synthetic HLA fields each yield correlation scales. Time periods with large internal waves show actual HLA signals with shorter length scale than the mode reconstructions (which display mode interference structure), which implies that the mode content is azimuthally varying. At times with no internal waves, the synthetic and actual HVLA fields are more similar. The apparent azimuthal variation in the high internal wave case provides a measure of the horizontal correlation scale imposed by the internal waves, measured even at broadside, when mode interference disappears. Coherence scale results, for comparison with theory (Duda, 2006) are: With internal waves, 75 m, 5 wavelengths. No internal waves: 220 m, 15 wavelengths.

## IMPACT/APPLICATIONS

The application of the results may be in the signal processing domain, since algorithms may be developed that are robust signal fluctuations or may exploit them. For example, processing might exploit fluctuations by utilizing intermittent but strong signal peaks, or predicting time limits for coherent analysis, or predicting wait intervals to reacquire signals after fade-outs.

## RELATED PROJECTS

At this time the PI is a participant in the LEAR portion of SW06, and is currently processing and examining the data from the order-50 moorings that collected water-column variability in the area of the acoustic experiments. We are working with D. Knobles (ARL-UT) and H. DeFerrari (Miami) to examine the environment during their propagation experiments, and with Lynch (WHOI) and Badiey (U Del.). The ONR postdoctoral awardees Y.-T. Lin (WHOI) and Jon Collis (Boston University) are working on LEAR/SW06 propagation issues under separate funding, in coordinated fashion. The PI is working with NLIWI ONR Physical Oceanography PI's analyzing data from the SW06 and 2007 South China Sea experiment sites.

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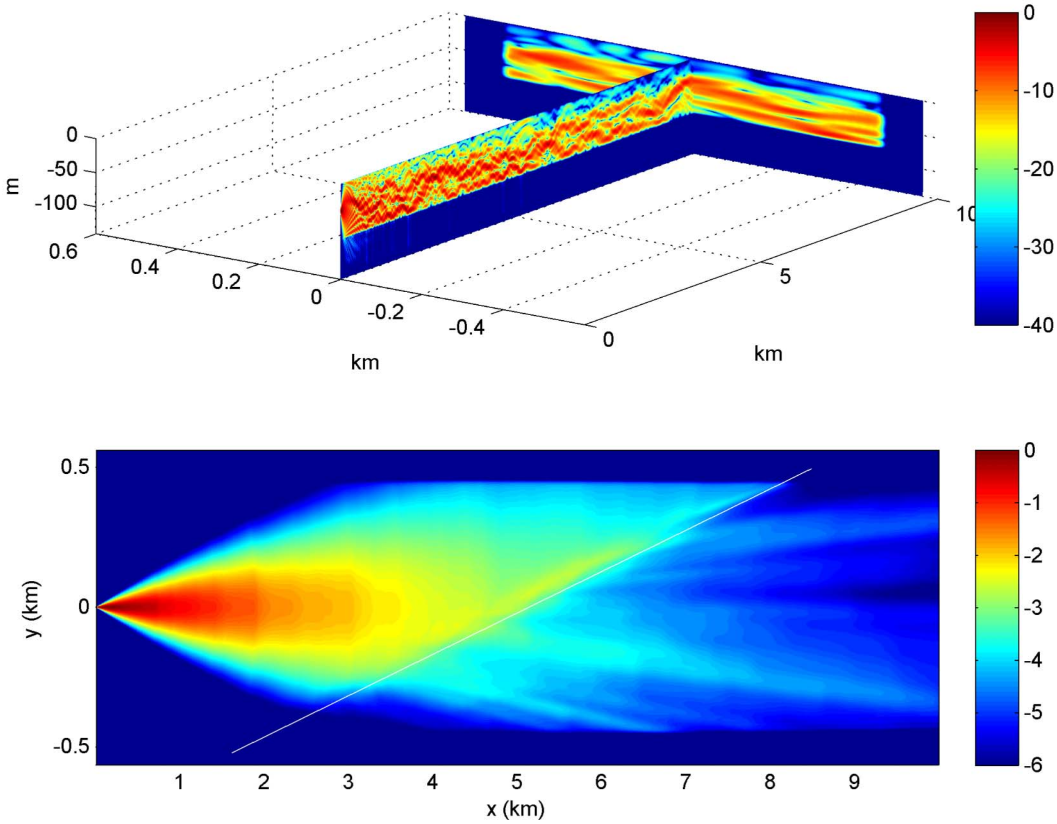
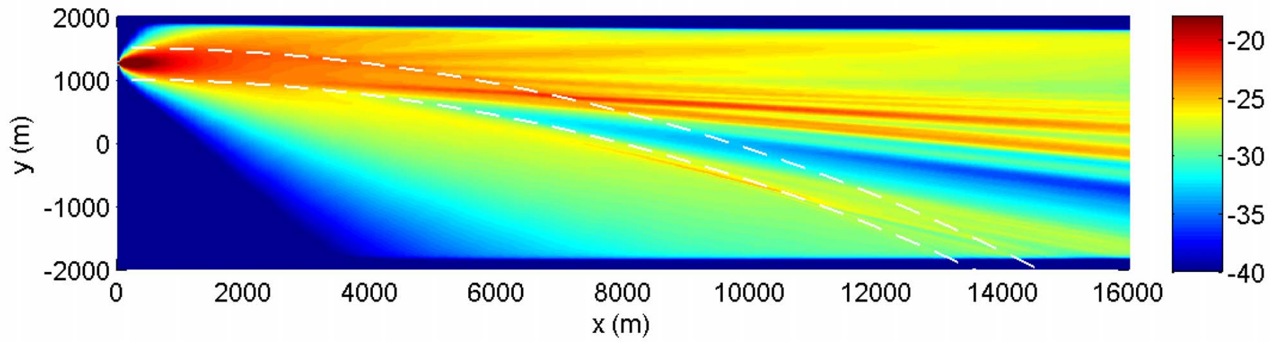



***Figure 1: Results from the 3D PE model are shown for a scenario of near-grazing transmission through a single internal wave. (Upper panel) Sound intensity (dB, arbitrary) is shown in a radial slice from the source at (0,0,-40) m, and in a tangent plane at range 10 km. (Lower panel) The color shows depth-averaged sound intensity (dB, arbitrary). The white line shows the position of the internal wave (nonlinear solitary wave of displacement). In both panels intensity has been multiplied by range to adjust for spreading loss. Conditions: 80-m water depth; 82 degree internal wave angle in the domain, internal wave shape $B\text{sech}^2(x/C)$, B=20 m, C=70m, 400-Hz sound, 1024 x 1024 split-step computational domain of width 300$\lambda$, height 75$\lambda$ including image domain), range step 2$\lambda$. This situation, propagation through a single internal wave similar to the largest seen in the SW06 experiment, shows concurrent horizontal deflection of sound and mode coupling (radial streaks). [The upper panel shows a 2D vertical slice of sound intensity showing typical modal interference pattern evolving with radial distance from the source. At 10-km distance from the source the field shows lateral structure. The lower panel shows a high-intensity streak of sound laterally refracted by the wave, and azimuthally varying intensity which is a signature of mode coupling behavior.]***



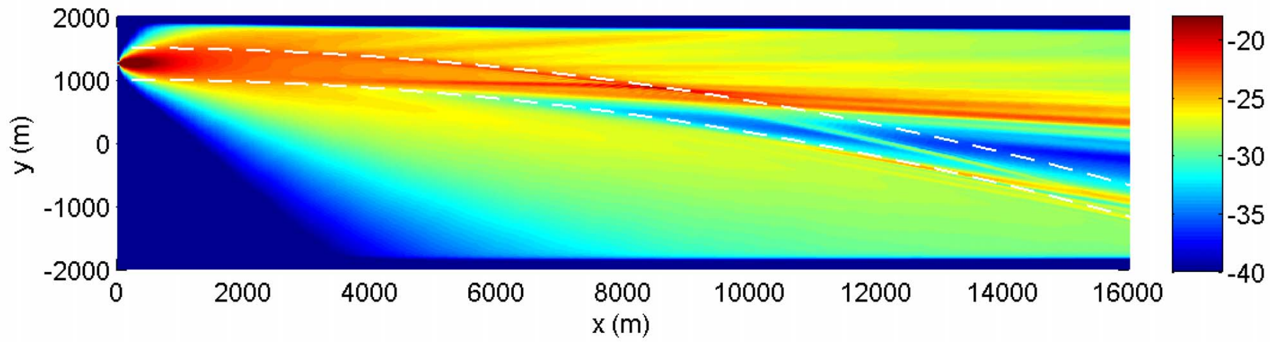




***Figure 2: Results are shown for sound propagation though pair of curved internal waves. Depth-averaged intensity computed with the 3D PE model is shown (dB, arbitrary). The sound source is between the two waves of thermocline depression, marked with the white dashed lines. Refraction of sound by the waves caused shadow zones and intense beams. The highly curved wave (upper) clearly shows multiple beams that may indicate differential refraction of modes, a prism effect. The less curved wave (lower) shows this also, also shows secondary beams that follow the waves at ranges greater than 10 km. [ The sound intensity, shown with color, exhibits shadow zones (blue, -40 dB) and high-intensity beams (red, -20 to -25 dB) that are caused by refraction of sound by the internal waves. The domain has a downrange length of 16 km, a cross-range length of 4 km.***

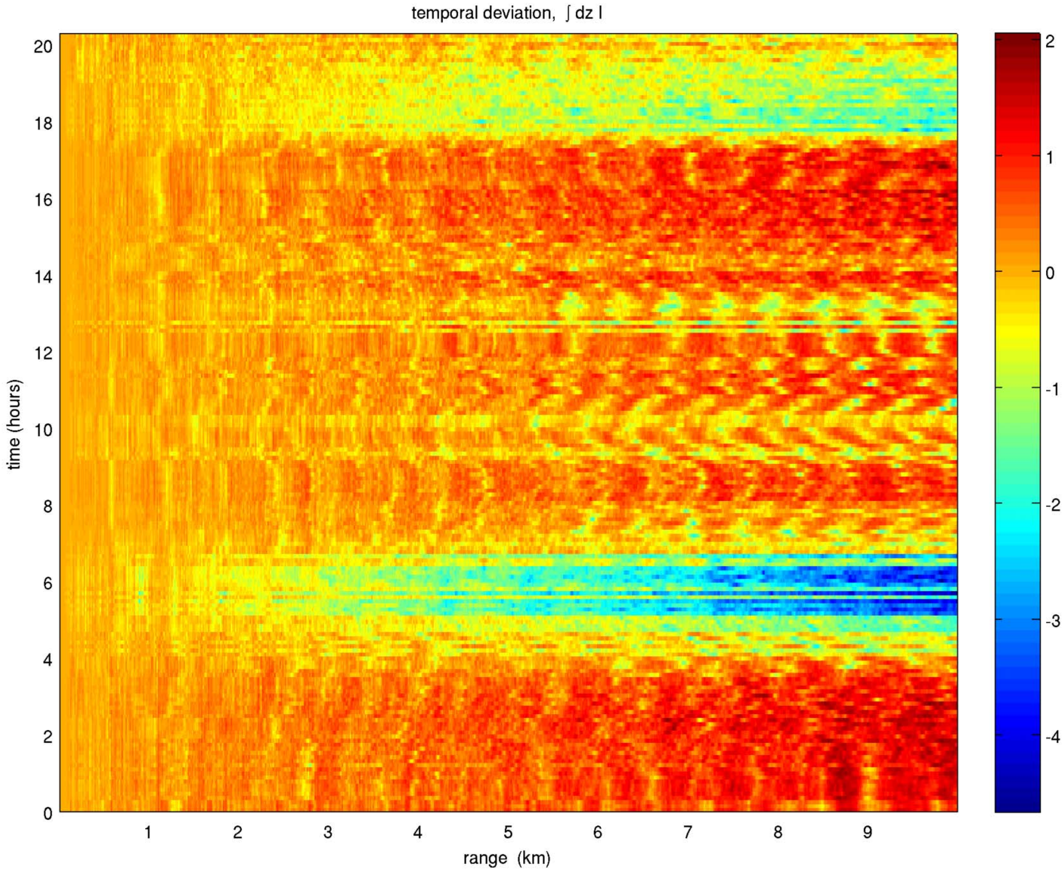



***Figure 3: Results from a time series of 900-Hz PE simulations along a fictitious path in the SW06 experimental domain are shown. Depth-averaged intensity is shown, with the temporal mean level for each range subtracted away to reveal only the temporal variation. A 6 dB range is seen 9 to 10 km from the source. The evolving 2D sound-speed field is derived from a mooring time series converted to a 2D spatial slice assuming the internal tide and non-linear internal waves travel with projected phase velocity of 0.78 m/s along the acoustic path. [The x axis is range from source 0-10 km. The y axis is time, 0 to 20 hours. Near the source the intensity level remains near 0 dB. At the right, far from the source, the intensity varies from -4 to +2 dB (blue to dark red). The temporal variation creates low-intensity horizontal streaks that are blue at the right for times 5-7 hr and 18-20 hr, and high-intensity dark streaks at 0-3 hr and 15-17 hr.]***

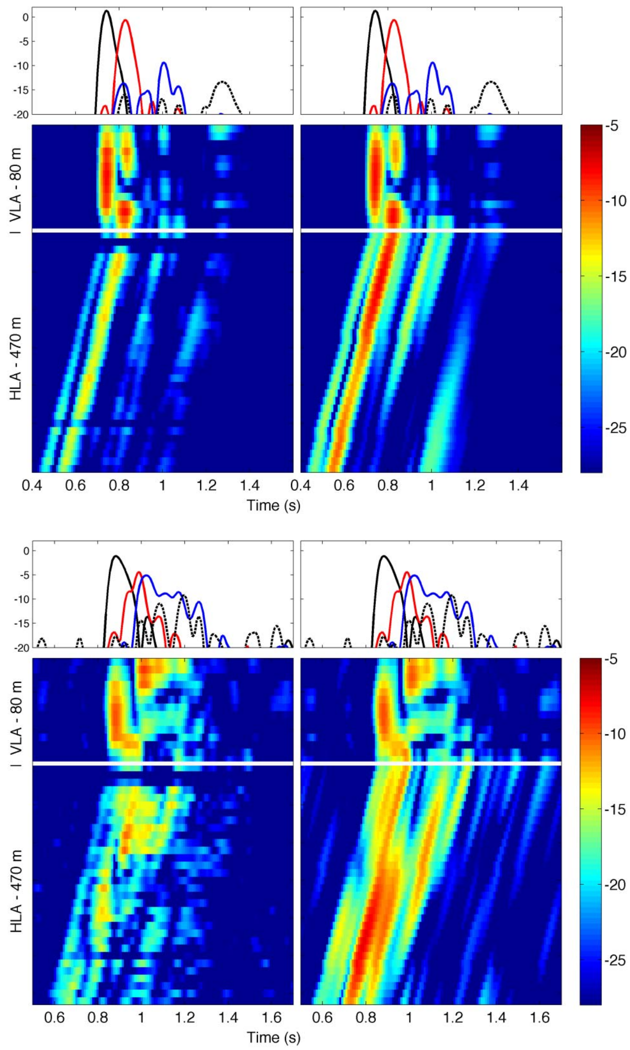



***Figure 4. Arrivals of 100-Hz sound at the SW06 WHOI HVLA are shown. (Lower panel, of two) Sound from a period of large internal waves is shown at the left, in color (dB, arbitrary). Time series of 1.2 s duration are shown for the entire L-shaped HVLA, starting at the bottom with the tail end of the HLA, moving upward to the junction with the VLA, and then upward along the VLA. The HLA-VLA junction is marked with a white line. Sound arrives first at the tail end of the HLA, last at the VLA; the sound bearing is approximately 25.6 deg. from HLA endfire. Above the color intensity plot is VLA mode filtering output, modes 1-4 (black, red, blue, dash black). To the right the reconstruction of the VLA and HLA signals using only the fitted modes is shown. The synthetic HLA field has larger scale lengths than the actual field, indicating azimuthal variation in mode amplitude and phase of the arriving signal. (Upper panel) the same type of display is shown for a period of weak internal waves. The measured and synthetic HLA signals are more similar than in the other case. Also, modes are dispersed nicely. [ Time period of small internal waves shows coherent arrivals along the HLA, the period of larger internal waves does not. The small internal wave period shows dispersed modes, the other shows overlapping multiple mode arrivals.]***